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Factors Affecting Zinc Uptake in Cropping Systems

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ABSTRACT

Zinc availabilities can change with different cropping management practices. The objective of this study was to identify some of the causative factors associated with previous crops contributing to Zn uptake differences in a subsequent crop. Field studies over 3 yr evaluated the Zn availability after four precropping treatments: bean (*Phaseolus vulgaris* L.), corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), and fallow, across two Zn fertilization rates (with and without 11 kg Zn ha^{-1} as $ZnSO_4$), using the 'Viva' bean as a test crop. Soil samples taken before and after the test crop were analyzed for extractable P, Zn, Cu, Mn, and Fe, and organic matter. Soil respiration during the test crop was periodically estimated the last cropping year. Whole plant samples estimated nutrient concentration and uptake. Soil Zn extracted by diethylenetriaminepentaacetic acid (DTPA) was increased by Zn fertilization but not affected by precropping treatments. Zinc uptake by bean was significantly higher after precropping with corn and lower after fallow regardless of Zn fertilization. Uptake differences were most pronounced during early plant growth. Phosphorus and Cu uptake varied with treatment in a similar pattern as Zn uptake, and were positively correlated with each other. Zinc uptake was also positively correlated with soil organic matter and negatively correlated with soil P. Soil respiration rate was significantly lower after the fallow treatment compared with other precropping treatments. Vesicular-arbuscular mycorrhiza (VAM) colonization in the test crop roots was higher after corn and lower after fallow regardless of soil Zn concentrations. Colonization was positively correlated with Zn, P, and Cu uptake during early plant growth. The VAM colonization, soil respiration, and DTPA-extractable Zn were selected by a stepwise regression procedure as the important variables affecting Zn uptake during early plant growth. These results emphasize the importance of the soil's biological activities on Zn availability and may help explain some field observations where chemical soil tests appear to fail.

THE PLANT AVAILABILITY of soil Zn partially depends on the previous crop grown. Leggett and Westermann (1986) observed that Zn deficiency in bean was greater than expected where the field was fallowed the previous year and extractable soil Zn concentrations were marginal. Bean grown after sugarbeet (*Beta vulgaris* L.) and fallow also had less Zn uptake compared with those following corn. Formation of organic–Zn complexes and P–Zn interactions were proposed to explain Zn deficiency in crops following sugarbeet or fallow (Smith and Shoulkry, 1968; Ellis et al., 1964; Boawn, 1965). It is unknown how important other nutrient interactions and microbiological associations were in their studies. About 60% of the available soil Zn forms complexes with the soluble organic matter (Hodgson et al., 1966). Martens et al. (1966) showed a high positive correlation between organic matter and 0.1 *M* HCl-extractable Zn. Loneragan et al. (1979) reported Zn-deficiency-like symptoms in subterranean clover (*Trifolium subterraneum* L.) following P applications. Zinc deficiency in corn is often aggravated by P fertilization, especially on calcareous soils (Langin et al., 1962).

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Abbreviations: VAM, vesicular-arbuscular mycorrhiza; DTPA, diethylenetriaminepentaacetic acid.

Vesicular-arbuscular mycorrhizae inoculation can sometimes increase Zn uptake and eliminate Zn deficiency symptoms (Bowen et al., 1974; Neilsen and Jensen, 1983). Long-term storage of topsoil reduces viable mycorrhizal fragments (Rives et al., 1980) and spore viability (Daniels and Menge, 1980). Fallowing may reduce the inoculum potential of a soil in a similar fashion (Cooper, 1984). Black and Tinker (1979) found that 1 yr of fallow or nonhost cropping reduced colonization 50% in a subsequent barley (*Hordeum vulgare* L.) crop. Precropping with a VAM host crop increased VAM colonization in the same or another host grown afterward (Ocampo, 1980; Smith, 1980; Black and Tinker, 1979).

The objectives of this study were to: (i) examine the effects of 1 yr of cropping or fallow on Zn uptake by a subsequent bean crop and (ii) evaluate the relationships between selected biological and chemical factors associated with the previous crop and Zn availability.

MATERIALS AND METHODS

Three experiments were conducted on a Portneuf silt loam (coarse-silty, mixed, mesic Durixerollic Calciorthid) near Kimberly, ID. In Exp. 1 (1986) and 2 (1987), bean, corn, wheat, and fallow treatments were established in a randomized complete block design with four replicates. In Exp. 3 (1988), only bean, corn, and fallow treatments were used. All plots within an experiment were uniformly fertilized before establishing the precropping treatments. Following removal of all aboveground plant biomass in the fall, all plots were randomly split and 11 kg Zn ha^{-1} sprayed on one-half as $ZnSO_4$ at 250 L ha^{-1}. The entire experimental area was then plowed to a depth of 0.25 m. No additional fertilizer was applied before planting the test crop of Viva bean the next spring. This cultivar is moderately susceptible to Zn deficiency (Brown and Leggett, 1967). The seed used for the test crop was not treated with inoculum or fungicides. Bean roots are well nodulated by indigenous rhizobia. Interrow spacing for bean, corn, and wheat was 0.56, 0.76, and 0.18 m, respectively. All plots within an experiment were furrow irrigated for the same length of time according to the soil moisture status determined with a tensiometer placed in the row at 0.3 m. Final test crop seed yields were evaluated by harvesting two 7.6-m rows.

Data were analyzed by using analysis of variance procedures for a split-plot, completely randomized, block design with three replications. Mean comparisons were made with the least significant difference procedure (Steel and Torrie, 1980). Relationships were also evaluated by simple linear and stepwise multiple regression techniques.

Soil Methods

Soils were sampled from all treatments the fall after harvesting the differential crops but before applying Zn fertilizer, the following spring before emergence of the test crop (bean), and after harvesting the test crop the next fall. Ten to twelve cores (0.016-m diam. and 0.3 m deep) were randomly taken within each subplot, combined, dried in a forced air drying cabinet at 38 °C, and pulverized in a stainless steel flail grinder to pass through a 0.002-m sieve.

Soil Zn, Cu, Mn, and Fe concentrations were extracted with DTPA and determined by atomic absorption spectrophotometry (Lindsay and Norvell, 1978). Soil P was extracted with $NaHCO_3$ (Olsen and Sommers, 1982) The $NaHCO_3$ extract was diluted (9:1) with concentrated HNO_3 and K concentrations determined by atomic absorption spectrophotometry. Soil organic C was determined by the Walkley–Black procedure (Nelson and Sommers, 1982), assuming that 50% of the soil organic matter was organic C. Soil pH was determined on a saturated soil paste.

Table 1. The DTPA-extractable soil Zn concentrations in the 0- to 30-cm soil depth before planting the test crop.

Treatment	Experiment 2	Experiment 3
	mg kg^{-1}	
Previous crop		
Beans	1.93 a†	0.69 a
Wheat	1.89 a	—
Fallow	2.04 a	0.80 a
Fertilization		
+ Zinc	2.68 y	0.89 y
− Zinc	1.34 x	0.56 x
	ANOVA significance levels	
Source		
Crop	$P = 0.84$	$P = 0.37$
Zinc	$P = 0.00$	$P = 0.01$
Interaction	$P = 0.72$	$P = 0.80$

† Means with similar letters within columns within experiments are not significantly different at the 0.05 level based on LSD multiple comparisons.

Soil respiration rate was estimated by measuring CO_2 evolution five times during the test crop in Exp. 3 (Anderson, 1982). Open glass jars with 0.02 L of 1.0 *M* NaOH were placed on the soil surface between rows in each half plot. The jars were covered with white (18.9 L, 0.14-m diam.) plastic buckets pushed into the soil 0.03 to 0.04 m. An attempt was made to avoid covering any emerging bean or weed plants. After 24 h, the jars were closed and the unreacted base titrated with 1.0 *M* HCl.

Plant Methods

Whole plant tops of each previous crop were sampled in Exp. 2 and 3 before harvest. A 1.5-m bean row, a 3-m corn row, and a 1-m^2 area of wheat were randomly sampled from each of the plots. The plant tops were weighed, dried at 60 °C in forced-air ovens, weighed again, shredded, and subsampled for additional processing. At various stages of plant development (LeBaron, 1974) in the test crop, 10 whole bean plant tops were randomly sampled from each subplot, washed in distilled water, dried at 60 °C, and weighed. A 1.5-m row was sampled from each subplot just before seed harvest and processed in the same manner. All dried plant samples were ground in a stainless steel grinder to pass through a 425-μm^2 stainless steel screen.

The plant samples were digested with $HClO_4$ and HNO_3, filtered, and Cu , Mn, Fe, Zn, Ca, Mg, and K concentrations determined in the filtrates with an atomic absorption spectrophotometer (Isaac and Kerber, 1971); P concentrations were determined colorimetrically (Kitson and Mellon, 1944); and S concentrations were determined turbidimetrically (Westermann, 1975). Total N concentrations were determined by the Kjeldahl procedure (Bremner and Mulvaney, 1982).

Root Sampling and VAM Assessment

Bean roots were assayed for VAM colonization once in Exp. 2 and three times in Exp. 3 on dates corresponding with plant samplings. A 0.6-m row of plants the depth of the root zone at that stage of growth was carefully uprooted from each subplot and the loose soil gently shaken from the roots. Plant tops were excised at the cotyledonary node and all roots washed on a fine mesh screen (180 μm) with distilled water until the visible soil was gone. The largest, woody suberized roots were removed and the remaining roots cut in about 0.01-m segments, cleared with KOH, and stained with trypan blue in lactophenol (Phillips and Hayman, 1970). The root length per-

Table 2. Preplant soil analysis means and ranges combined across all treatments. There were no significant effects of treatment or Zn applications.

Experiment		Organic matter	Mn	Fe	Cu	P
		g kg^{-1}	mg kg^{-1}			
1	Mean	12.6	4.2	6.6	1.1	12.2
	Range	11.6–13.7	3.7–5.3	5.7–7.8	0.9–1.2	8.7–16.5
2	Mean	12.4	6.2	6.0	1.0	8.8
	Range	11.0–14.2	5.3–7.4	4.5–8.1	0.7–1.3	5.3–14.5
3	Mean	11.8	7.6	11.2	1.3	13.6
	Range	9.7–13.1	6.4–8.9	9.5–12.5	1.2–1.4	9.8–23.5

centage colonized by VAM was estimated by visually examining 100 root segments in a subsample of the stained roots (Biermann and Linderman, 1981).

RESULTS

In Exp. 2 and 3, DTPA-extractable soil Zn concentration in the spring of the test crop years was not affected by the previous crop, but was higher after Zn fertilization (Table 1). A significant Zn × crop interaction for extractable soil Zn only occurred in Exp. 1 (data not shown). The DTPA soil Zn concentrations in the fall after the test crop year were not different from the spring concentrations (data not shown). There was no treatment effect (cropping or Zn fertilization) on the preplant soil concentration of P, Cu, Mn, Fe, and organic matter for the test crop year of each experiment (Table 2). The range in concentrations is due to apparent spatial and sampling variability. Soil pH was nearly the same in all experiments, 7.8 ± 0.2.

In all experiments, Zn deficiency symptoms were present during early plant development after fallow, regardless of Zn fertilization, and also in some plots having relatively low soil Zn concentrations. Chlorosis, leaf mottling, stunted growth, and trifoliate curling symptoms were pronounced in Exp. 3. Most plants grew out of these symptoms with advanced growth, but plant maturity was delayed. Final seed yields within an experiment were not affected by any treatment (data not shown).

Plant Zn concentration of the bean test crop was significantly higher after corn and lower after fallow compared with after bean, for all sampling dates in Exp. 3 (Fig. 1). Plant dry weights also tended to be lower after fallowing, compared with bean grown after corn or bean, although the difference was significant only for the third sampling date, 10 July 1989 (Fig. 2). Representative data are only shown from Exp. 3 in Fig. 1, 2, and 3, as results were similar for the other years. Zinc concentrations and dry weights of plants grown after wheat were usually between those after corn and bean (data not shown). Zinc uptake was higher after corn than after bean for the first two sampling dates, and lower after fallow for all dates (Fig. 3). These precropping treatment effects cannot be easily explained by dilution or concentration effects since both plant dry weights and Zn concentrations were lower after fallowing. Plant Zn concentrations were consistently higher in the Zn-fertilized treatments compared with the non-Zn treatments in all experiments (data not shown). There were no significant Zn × crop interactions for plant Zn concentration or dry weight. These experiments verified the findings

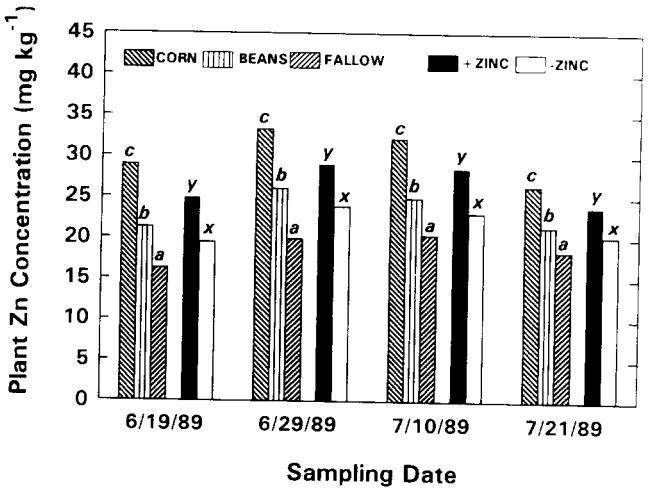

Fig. 1. Previous crop and Zn fertilization effects on bean Zn concentrations (Exp. 3). A different letter between cropping or Zn treatments within a sampling date indicates a difference at the $P = 0.05$ level.

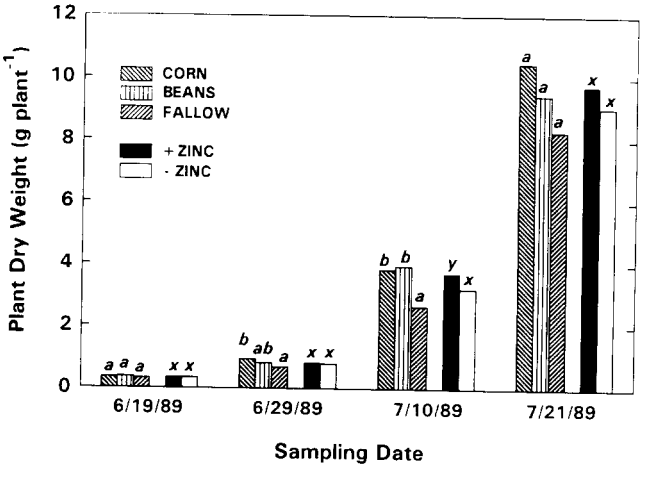

Fig. 2. Previous crop and Zn fertilization effects on bean plant dry weights (Exp. 3). A different letter between cropping or Zn treatments within a sampling date indicates a difference at the $P = 0.05$ level.

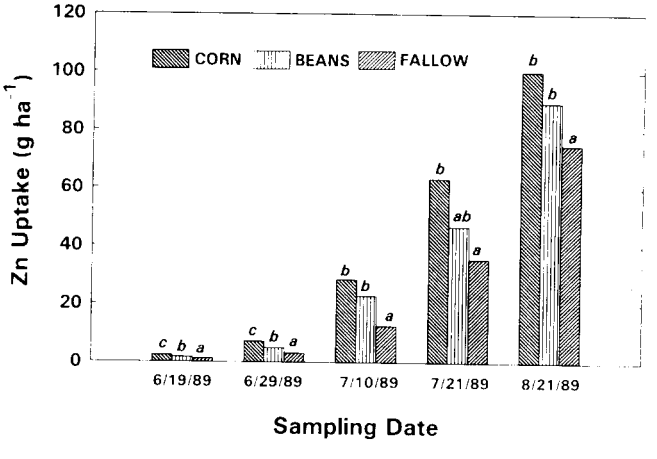

Fig. 3. Previous crop and Zn fertilization effects on Zn uptake (Exp. 3). A different letter between cropping or Zn treatments within a sampling date indicates a difference at the $P = 0.05$ level.

Table 3. Sampling date, growth stage, and linear correlation coefficients probability level in parentheses between Zn uptake and soil Zn, P, and organic matter concentrations.

Experiment	Sampling date	Growth stage	Correlation coefficient		
			DTPA-Zn	$NaHCO_3$-P	Organic matter
1	1 July 1987	V5	0.213 (0.14)	−0.512 (0.00)	0.512 (0.00)
	14 July 1987	V7-V8	0.258 (0.01)	−0.431 (0.00)	0.456 (0.00)
	21 July 1987	R2	0.182 (0.43)	−0.426 (0.00)	0.363 (0.00)
	21 Aug. 1987	R8-R9	0.186 (0.19)	−0.214 (0.13)	0.019 (0.99)
2	29 June 1988	V5	0.191 (0.32)	−0.696 (0.00)	0.580 (0.00)
	11 July 1988	R1	0.347 (0.00)	−0.602 (0.00)	0.457 (0.00)
	22 July 1988	R2-R3	0.470 (0.00)	−0.578 (0.00)	0.638 (0.00)
	23 Aug. 1988	R8-R9	0.267 (0.01)	−0.491 (0.00)	0.318 (0.00)
3	19 June 1989	V1-V2	0.232 (0.26)	−0.273 (0.07)	0.237 (0.22)
	29 June 1989	V4	0.112 (0.99)	−0.289 (0.04)	0.350 (0.00)
	10 July 1989	V8-R1	0.120 (0.99)	−0.348 (0.00)	0.273 (0.07)
	21 July 1989	R3-R4	0.154 (0.92)	−0.155 (0.91)	0.379 (0.00)
	21 Aug. 1989	R8-R9	—	—	—

Table 4. Precropping effects on plant Cu and P concentration and uptake (Exp. 3).

Precropping treatment	19 June 1989				29 June 1989			
	Cu		P		Cu		P	
	concentration	uptake	concentration	uptake	concentration	uptake	concentration	uptake
	mg kg^{-1}	g ha^{-1}	g kg^{-1}	kg ha^{-1}	mg kg^{-1}	g ha^{-1}	g kg^{-1}	kg ha^{-1}
Corn	15.0 c†	1.2 b	4.0 c	0.32 b	15.3 c	3.3 b	4.2 b	0.90 b
Bean	12.1 b	1.0 b	3.2 b	0.27 b	14.0 b	2.6 b	3.9 ab	0.74 ab
Fallow	8.3 a	0.6 a	2.3 a	0.17 a	11.5 a	1.8 a	3.4 a	0.53 a

† Means with similar letters within columns are not different at the 0.05 probability level based on LSD multiple comparisons.

of Leggett and Westermann (1986) that Zn uptake by bean increased following corn and decreased after fallowing compared with after bean or wheat, regardless of Zn fertilization rates.

The DTPA-extractable soil Zn was not consistently correlated with Zn uptake in any experiment (Table 3). Wheat removed more Zn than either corn or bean in Exp. 2 (299.6, 209.0, and 152.7 g ha^{-1}, respectively). This is inconsistent with the Zn uptake patterns observed in the subsequent bean crop. In general, the decrease in Zn uptake after fallow cannot be explained by differential precrop Zn removal or by lower DTPA-extractable soil Zn concentrations.

In all experiments, soil P concentrations were negatively correlated with Zn uptake, while organic matter concentrations were positively correlated (Table 3). The DTPA-extractable soil Zn was weakly correlated with organic matter concentration (r = 0.17, 0.24, and 0.33 for Exp. 1, 2, and 3, respectively).

Precropping treatments effects on early plant Cu and P concentration and uptake were similar to those for Zn (Table 4). These differences continued through early bloom but were no longer significant by late bloom (V8–R1) and early pod development (R3–R4). The pattern was similar in Exp. 1 and 2; however, the duration and significance of the differences varied with experiment (data not shown). Concentration and uptake of Cu and P were not different between Zn treatments and there were no significant Zn × crop interactions. The similarity in Cu, P, and Zn responses to precropping treatments suggests that their availabilities were being controlled by similar processes.

Soil respiration rates during bean emergence and early development in Exp. 3 were consistently lower in the fallow treatment than in the bean and corn treatments (Fig. 4). There was no significant effect of Zn application on soil respiration and no Zn × crop interaction. Soil respiration rates correlated with Zn uptake (Table 5).

Fallow and corn treatments had lower VAM colonizations than the bean treatment in Exp. 2 (Table 6). Mean root length colonized by VAM was relatively high for all treatments in Exp. 2, probably because the roots were collected during rapid root growth when extensive development of VAM is expected (Sutton, 1973). Differences between treatment will probably decrease as VAM colonization becomes more extensive. Root length per-

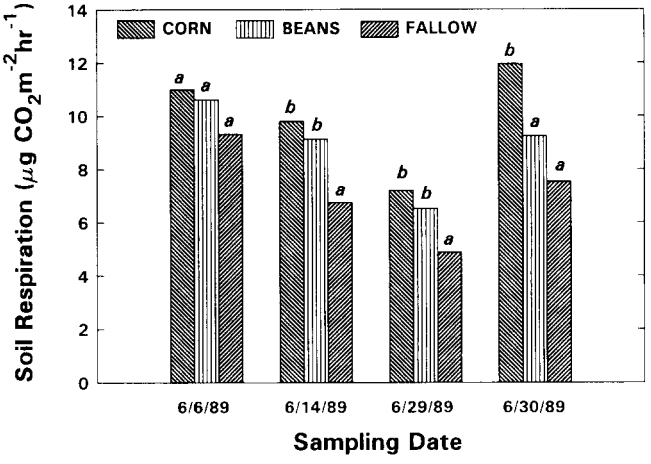

Fig. 4. Cropping treatment effects on soil respiration rate (Exp. 3). A different letter between cropping or Zn treatments within a sampling date indicates a difference at the P = 0.05 level.

Table 5. Linear correlation coefficients between soil respiration and Zn uptake at different sampling dates (Exp. 3).

Variables			Correlation coefficient
CO_2 evolution on 6 June 1989	with	Zn uptake by 19 June 1989	$r = 0.23$ ($P = 0.28$)
CO_2 evolution on 14 June 1989	with	Zn uptake by 19 June 1989	$r = 0.54$ ($P = 0.00$)
CO_2 evolution on 23 June 1989	with	Zn uptake by 29 June 1989	$r = 0.49$ ($P = 0.00$)
CO_2 evolution on 30 June 1989	with	Zn uptake by 29 June 1989	$r = 0.80$ ($P = 0.00$)
CO_2 evoltuion on 7 July 1989	with	Zn uptake by 10 July 1989	$r = 0.74$ ($P = 0.00$)

centage colonized by VAM in Exp. 2 was correlated with Zn, Cu, and P uptake (Table 7). Root sampling dates were chosen in Exp. 3 in an attempt to quantify VAM colonization before extensive root development obscured treatment differences. Mean root length percentage colonized with VAM was significantly higher after corn and lower after fallow than after the bean precropping treatment during early plant growth in Exp. 3 (Table 6). There were no significant differences on the third sampling date (10 July 1989); however, fallow tended toward lower VAM colonizations. The precropping effects on VAM colonization coincided with the observed Zn uptake (Fig. 3). Zinc uptake correlated with VAM colonization for the two earlier samplings but not for the later sampling (Table 7). The VAM colonizations also correlated with P and Cu uptake for the first two samplings.

DISCUSSION

Soil temperature and moisture conditions optimum for plant growth are generally also optimum for mycorrhizal growth. A three-phase pattern of mycorrhizal development occurs: an initial lag period, a period of extensive development, and a phase where the proportion of mycorrhizal roots to nonmycorrhizal roots is relatively constant (Sutton, 1973). The lag period of mycorrhizal colonization usually coincides with adverse spring conditions before extensive plant growth begins. Zinc deficiency symptoms noted in this and other studies (Bauer and Lindsay, 1965) are greater in the early spring, under cool, wet conditions. Zinc applications had no effect on VAM colonization nor was the Zn × crop interaction significant at any sampling date. Spring soil Zn concentrations (DTPA-extractable) were not correlated with VAM colonization (data not shown).

Table 6. Effect of previous crop and Zn fertilization on mean percentage root length colonized by VAM.

	Exp. 2	Exp. 3		
Treatment	29 June 1988	19 June 1989	29 June 1989	10 July 1989
	%			
Previous crop				
Corn	51 a†	43 c	60 c	33 a
Beans	64 b	23 b	43 b	35 a
Fallow	49 a	8 a	19 a	24 a
Wheat	58 ab			
Fertilization				
−Zinc	55 x	23 x	43 x	28 x
+Zinc	57 x	27 x	38 x	34 x
	ANOVA significance levels			
Source				
Crop	0.03	0.00	0.00	0.49
Zn	0.33	0.19	0.33	0.35
Interaction	0.45	0.51	0.92	0.92

† Means with similar letters within a column are not significantly different at the 0.05 probability level based on LSD multiple comparisons.

The adverse effect of soil P on Zn uptake may be related to its effect on VAM colonization. In soils with low to marginal available P, increased VAM colonization increases P uptake. Phosphorus fertilization, however, reduces VAM colonization. This reduced VAM colonization may reduce uptake of other nutrients more dependent on CEC, such as Zn and Cu. In Exp. 3, extractable soil P concentration was negatively correlated with VAM colonization at the first sampling date ($r = -0.35$, $P < 0.01$). It has been demonstrated that mycorrhizal inoculation can eliminate Zn deficiency symptoms and increase Zn uptake (Bowen et al., 1974; Gilmore, 1971; Neilsen and Jensen, 1983), and that uptake and translocation of Zn to plant roots occurs via mycorrhizal hyphae (Cooper and Tinker, 1978).

The DTPA-extractable soil Zn was poorly related to the Zn uptake differences caused by the previous cropping practices in this study. This confirms the observations made by Leggett and Westermann (1986). Soil Zn extracted by a resin was shown to be linearly related to DTPA-extractable Zn, but better related to Zn uptake than DTPA (Hamilton and Westermann, 1991). The resin may be extracting some labile Zn not extracted by the DTPA. The correlation of both methods with Zn uptake improved when evaluated within a cropping system.

The observed relationship between VAM colonization and Cu, P, and Zn uptake suggests that the precropping treatment effects were partially caused by differences in biological activity rather than chemical availability. Mycorrhizal fungi extend into pools of labile P, Cu, and Zn not accessed by nonmycorrhizal roots. The strong positive intercorrelation between P, Cu, and Zn uptake may also be attributed to their dependence on VAM exploitation. This observation helps explain the poor correlations between DTPA-extractable soil Zn and plant Zn uptake across different precropping treatments.

We used a stepwise regression procedure to relate Zn uptake in Exp. 3 to preplant soil concentrations of P, Zn, and organic matter, soil respiration rates (CO_2 evolution rates), and VAM colonization. For Zn uptake at the earliest sampling (V1–V2, 19 June 1989), forward selection included soil respiration as the first independent variable, soil Zn concentration second, and VAM colonization third. Soil P and organic matter concentrations were not selected. A backward selection procedure produced the same model. The final model selected for Zn uptake was: Zn uptake $= -1.06 + 0.19\ CO_2$ (μg cm $^{-2}$

Table 7. Linear correlation coefficients probability level in parentheses between VAM colonization and Zn, Cu, and P uptake.

Experiment	Sampling date	Zn	Cu	P
2	29 June 1988	0.302 (0.00)	0.342 (0.00)	0.455 (0.00)
3	29 June 1988	0.504 (0.00)	0.634 (0.00)	0.660 (0.00)
3	10 July 1989	0.101 (0.99)	0.276 (0.06)	0.251 (0.15)

h^{-1}) + 1.3 DTPA Zn (mg kg^{-1}) + 0.01 VAM (length T); adjusted R^2 = 0.52, mean squared error = 0.18, P = 0.0004.

Models predicting Zn uptake at later plant growth stages included fewer variables; for the next two sampling dates, 29 June and 10 July 1989, both forward and backward stepwise regressions selected only soil respiration rate. The omission of VAM emphasizes the contribution of VAM colonization to Zn uptake during early plant growth. Increased root activities may also be reflected in the later soil respiration measurements.

If VAM activity and soil respiration are interrelated, then only one variable should be included in the model. However, soil respiration may provide some unique information related to biological Zn cycling and the formation of natural chelates. Soil respiration, as measured in this study, probably reflects the biological activity associated with the decomposition of the previous crop residues. In addition, the composition and diversity of the microbiological community may depend on the previous crop. These differences could have significantly different effects on nutrient availabilities.

These data accentuate the importance of soil biological activity on Zn availability through the decomposition of organic Zn compounds or the formation of Zn chelates. The VAM colonization was also important for early plant Zn uptake. Differences in Zn availability with differential cropping reflect differences in VAM inoculum potential created by the previous crop. Both microbiological cycling and VAM exploitation of nutrients contributed to the observed differences in Zn, Cu, and P uptake in this study. Additional studies are needed to identify the roles that microbial mobilization and VAM mycelium and inoculum densities have in Zn uptake.

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